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Jitter Reduces Response-Time Variability in ADHD: An Ex-Gaussian Analysis

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Abstract

Objective—“Jitter” involves randomization of intervals between stimulus events. Compared with controls, individuals with ADHD demonstrate greater intrasubject variability (ISV) performing tasks with fixed interstimulus intervals (ISIs). Because Gaussian curves mask the effect of extremely slow or fast response times (RTs), ex-Gaussian approaches have been applied to study ISV.

Method—This study applied ex-Gaussian analysis to examine the effects of jitter on RT variability in children with and without ADHD. A total of 75 children, aged 9 to 14 years (44 ADHD, 31 controls), completed a go/no-go test with two conditions: fixed ISI and jittered ISI.

Results—ADHD children showed greater variability, driven by elevations in exponential (tau), but not normal (sigma) components of the RT distribution. Jitter decreased tau in ADHD to levels not statistically different than controls, reducing lapses in performance characteristic of impaired response control.

Conclusion—Jitter may provide a nonpharmacologic mechanism to facilitate readiness to respond and reduce lapses from sustained (controlled) performance.

Keywords

ADHD; executive function; attention; variability; response time; statistics; ex-Gaussian; jitter

Individuals with ADHD demonstrate deficient response control, manifested as slow and variable response times (RTs; Harris et al., 1995; Vaurio, Simmonds, & Mostofsky, 2009; Wodka et al., 2007). Over the past 15 years, impaired response inhibition has been considered the primary core feature of ADHD. More recently, however, studies point toward intrasubject variability (ISV), or moment-to-moment variability in each subject's RT series, as a more robust intermediate phenotype (Bidwell, Willcutt, Defries, & Pennington, 2007; Gomez-Guerrero et al., 2010). Individuals with ADHD demonstrate increased ISV

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compared with typically developing (TD) peers, suggesting inefficient response preparation and selection (Di Martino et al., 2008; Rommelse et al., 2008; Ryan, Martin, Denckla, Mostofsky, & Mahone, 2010).

Statistical methods have improved our approach toward the problem of RT variability. Traditional Gaussian analyses offer information regarding the mean and standard deviation of a given set of values. Because Gaussian curves can mask the effect of extremely slow or fast RTs, ex-Gaussian approaches have become increasingly popular among researchers investigating ADHD and other neuropsychiatric disorders (Hervey et al., 2006; Leth-Steensen, Elbaz, & Douglas, 2000; McAuley, Yap, Christ, & White, 2006; Vaurio et al., 2009). These ex-Gaussian methods model the mean (μ) of the normal distribution and the standard deviation (σ) of the normal distribution, as well as the mean and standard deviation of the exponential component of the distribution (τ). Thus, for RT series, τ indicates extremely prolonged RTs, which are thought to result from “lapses” from on-task behavior. Several studies have shown τ to be increased in ADHD compared with TD individuals across a range of tasks involving response control (Epstein et al., 2011; Hervey et al., 2006; Leth-Steensen et al., 2000; Vaurio et al., 2009). Furthermore, increases in σ were reported in tasks requiring higher response selection (Buzy, Medoff, & Schweitzer, 2009; Geurts et al., 2008; Vaurio et al., 2009). These findings suggest that ADHD is associated with increased RT variability represented in normal and exponential components of the distribution. As such, applying the ex-Gaussian approach may provide a more parsimonious representation of RT variability in children with ADHD.

Experimental paradigms that manipulate rate of event presentation and provision of incentives have demonstrated that ISV can be reduced in individuals with and without ADHD (Andreou et al., 2007; Kuntsi, Wood, van der Meere, & Asherson, 2009). Recent studies have applied interstimulus “jitter,” a technique involving randomization of time intervals between successive stimuli within a test series, to improve attentional and response control (Ryan et al., 2010; Wodka, Simmonds, Mahone, & Mostofsky, 2009). These studies compared performance under a fixed interstimulus interval (ISI) condition with that under a jittered (variable) ISI condition. In recently published findings by Ryan et al. (2010), under testing conditions of fixed ISI, individuals with ADHD showed increased ISV compared with controls. With the introduction of a moderate degree of jitter, ISV decreased in ADHD participants to levels not statistically different from controls.

The present study represents an extension and ex-Gaussian reanalysis of data presented in the Ryan et al. study, with 36 additional participants included in the present analysis, nearly doubling the sample size of the prior study. Because the standard summary variables produced in the Gaussian approach as performed in Ryan et al.'s study may not thoroughly represent the patterns of responses comprising the RT distribution curve (especially the exponential component), this reanalysis reflects a more comprehensive evaluation of RT variability in a larger cohort of children with ADHD. The aim of this study was to examine the effects of interstimulus jitter on the RTs of children with and without ADHD, examining the normal and exponential distributions. We hypothesized that, compared with TD controls, children with ADHD would show more variable RTs, with elevations in Gaussian (σ) and exponential (τ) components, when performing a go/no-go task under a fixed ISI task

condition. We also hypothesized that, with introduction of a moderate degree of interstimulus jitter, RT consistency would increase and the extreme lapses in attention would be reduced, as shown by decreases in both the variability in the normal (Gaussian) RT distribution (sigma) and exponential components of the RT distribution (tau).

Method

Participants

Participants were recruited from outpatient clinics at the Kennedy Krieger Institute, local schools, and pediatricians' offices, and enrolled as part of a larger study examining the brain mechanisms in ADHD. Informed consent was obtained for all study participants, in agreement with prior approval by the Johns Hopkins Medicine Institutional Review Board. Children between ages 9 and 14 years were screened by initial parent telephone interview to obtain demographic information, educational and developmental history, and medication status. Potential participants were excluded if there was a history of speech/language disorder or word reading difficulties identified either through telephone screening or prior school assessment completed within 1 year, evidence of visual or hearing impairment, history of other neurological disorder, or if they were taking psychotropic medications other than stimulants. Children who were taking stimulant medication were removed from medication on the day of and the day prior to testing. A total of 75 children (44 ADHD, 31 controls) were included in the present study.

Following telephone screening, parents were interviewed about their child using a structured psychiatric interview (i.e., Diagnostic Interview of Children and Adolescents–Fourth Edition [DICA-IV]). ADHD-oriented behavior rating scales, including the Conners' Parent Rating Scale–Revised/Conners' Teacher Rating Scale–Revised (CPRS-R/CTRS-R) and the ADHD Rating Scale–IV, were used to confirm diagnosis of ADHD. The diagnosis of ADHD was made using the following criteria: (a) Positive Diagnostic and Statistical Manual of Mental Disorders (4th ed., *DSM-IV*; American Psychiatric Association, 1994) ADHD diagnosis on DICA-IV, (b) *T*-scores greater than 65 on the *DSM-IV* Hyperactive/Impulsive or Inattentive scales of the CPRS-R or CTRS-R, and (c) six of nine *DSM-IV* symptoms met (item rating of 2 or 3) on the Hyperactive/Impulsive or Inattention scales of the ADHD Rating Scale–IV, Home or School Version. Children with *DSM-IV* diagnoses other than Oppositional Defiant Disorder and Specific Phobias were excluded. Parents of control participants completed the DICA-IV, CPRS-R, and ADHD Rating Scale–IV. Teachers of controls completed the CTRS-R and teacher form of the ADHD Rating Scale–IV. Controls with *T*-scores greater than 60 on either the *DSM-IV* Inattentive or Hyperactive/Impulsive scales of the CPRS-R or CTRS-R, or item ratings of 2 or greater for four or more symptoms of inattention or hyperactivity/impulsivity from the ADHD Rating Scale–IV (home or school), were also excluded. Children were excluded from the control group if they had a history of mental health services for behavior or emotional problems, history of academic problems requiring school-based intervention services, or history of defined primary reading or language-based learning disability. All participants were screened for word reading difficulties, which were defined as a score less than the 25th percentile on the Basic Reading Composite of the Woodcock Johnson–III (WJ-III) Tests of Achievement.

Children were administered the Wechsler Adult Intelligence Scale–IV (WISC–IV), the WJ–III reading tests, and the go/no-go test on the first day of assessment. The two conditions of the go/no-go test were administered in a counterbalanced sequence, with both groups experiencing the condition orders equally.

Demographics

Sample demographics are included in Table 1. The study included 75 participants: 44 with ADHD (27 male) and 31 controls (11 male), of whom 66.7% were Caucasian, 21.3% African American, 4.3% Asian, 1.3% Pacific Islander, and 6.7% mixed race. Within the ADHD group, there were 14 (31.8%) with Inattentive subtype, 0 with Hyperactive-Impulsive subtype, and 30 (68.2%) with Combined subtypes. DICA-IV assessments were obtained on 31 controls and none had comorbidities. For children with ADHD ($n = 44$), 16 (36.4%) met criteria for Oppositional Defiant Disorder and 3 (6.8%) met criteria for Specific Phobia. Of the ADHD participants, 26 (59.0%) were on one or more stimulant medications at the time of enrollment in the study. For ADHD participants not on medication, time since last medication use was not reported. Participants ranged in age from 9 to 14 years, with an average age of 11.2 years. There were no significant differences in racial distribution, $\chi^2(4) = 3.26, p = .516$, between ADHD and control groups. In addition, there were no significant differences between groups in age or socioeconomic status (SES); however, control participants demonstrated higher Full Scale IQ (FSIQ) scores than the ADHD group (Table 1). There was also a higher proportion of boys in the ADHD group than in the control group, $\chi^2(1) = 3.74, p = .053$. Sex was not significantly correlated with any of the six outcome variables (mean RT—RT, standard deviation of RT—SD, and coefficient of variability—CV, μ , σ , or τ) and, therefore, was not used as a covariate in analyses. In addition, given the overlap between components of FSIQ and the executive functions under investigation, especially those involving response preparation/processing speed, covarying for FSIQ was not considered appropriate when measuring group differences on components of the go/no-go test (Dennis et al., 2009). Furthermore, a recent meta-analysis of the effects of attention deficits on assessment of IQ noted that children with ADHD taking stimulant medications while being tested had a mean increase of 6 to 7 IQ points compared children with ADHD who were not taking stimulants during testing (such as those in the present study), suggesting that reduced IQ scores in our ADHD group may be driven by attentional problems and suboptimal test-taking behavior rather than reduced intelligence, per se (Jepsen, Fagerlund, & Mortensen, 2009). Therefore, we did not covary for FSIQ in the present analyses.

Measures

Go/no-go test. Participants completed a computer-based go/no-go paradigm in which red and green spaceships were presented. Each participant was instructed to use his or her dominant hand index finger to push a button immediately in response to green spaceships only. Familiar color elements such as green for “go” and red for “no-go” minimized the working memory load during the test. For a detailed description of the paradigm, the reader is referred to Ryan et al. (2010) and Wodka et al. (2007). Two conditions of the go/no-go test were administered. In the *fixed* ISI condition, cues appeared on the screen for 300 ms and were presented once every 1,500 ms. Presentation cues were weighted toward green

spaceships at a ratio of 3:1 (162 “go” cues and 54 “no-go” cues), intensifying the need to inhibit a habituated motor response. In the *jittered* ISI condition, stimuli were presented with a variable ISI, using a moderate (33.3%) level of jitter in which five ISIs were presented randomly, ranging from 1,000 to 2,000 ms (i.e., 1,000, 1,250, 1,500, 1,750, and 2,000). Higher or lower levels of jitter would contain longer or shorter ISI, respectively. The presentations were administered under the same sequence to all participants. The total time for each go/no-go condition was 6 min 30 s. Only “go” RTs were used, and RTs on failed inhibition trials were omitted from the analysis.

Data Analysis

Ex-Gaussian analyses were performed for the RT series to estimate the distribution parameters: mu, sigma, and tau. The analyses were performed using the egfit function in MATLAB (Lacouture & Cousineau, 2008). Only accurate responses (i.e., correct hits) were used in analyses of reaction time data (i.e., omitted responses or commission errors were not included). Repeated measures ANOVAs were used to examine the moderating effect of jitter on go/no-go test performance, and to compare performance between control and ADHD groups for accuracy (omissions and commissions), mu, sigma, and tau, as well as for CV and standard (Gaussian) mean RT components.

Results

There were no significant sex differences on any of the eight outcome variables ($p > .24$ for all comparisons). Therefore, data from boys and girls were combined for all subsequent analyses.

Children's performance across task conditions is presented in Table 2. For percent omissions, there was a significant effect for group (ADHD vs. control), such that children with ADHD had more omission errors than controls, $F(1, 72) = 5.17, p = .026, \eta_p^2 = 0.067$. The effects of condition (fixed vs. jittered), $F(1, 72) = 0.70, p = .792, \eta_p^2 = 0.001$, and the group-by-condition interaction, $F(1, 72) = 2.06, p = .156, \eta_p^2 = 0.028$, were not significant. For percent commission errors, a similar pattern emerged. The effect for group was significant, such that children with ADHD had more commission errors than controls, $F(1, 72) = 7.20, p = .009, \eta_p^2 = 0.091$. The effects of condition, $F(1, 72) = 0.75, p = .389, \eta_p^2 = 0.010$, and the group-by-condition interaction, $F(1, 72) = 0.009, p = .926, \eta_p^2 = 0.0001$, were not significant. Thus, children with ADHD perform worse than controls with regard to task accuracy, regardless of condition (fixed vs. jittered).

For mean RT, the effects for group, $F(1, 73) = 1.28, p = .26, \eta_p^2 = 0.017$; condition, $F(1, 73) = 0.10, p = .75, \eta_p^2 = 0.001$; and the group-by-condition interaction, $F(1, 73) = 0.590, p = .44, \eta_p^2 = 0.008$, were not significant (Figure 1a). For the standard deviation of RT (*SD*), there were significant effects for group (ADHD > control), $F(1, 73) = 6.99, p = .01, \eta_p^2 = 0.087$, and condition (fixed > jittered), $F(1, 73) = 13.32, p < .001, \eta_p^2 = 0.154$. The group-by-condition interaction was not significant, $F(1, 73) = 2.97, p = .089, \eta_p^2 = 0.039$.

Mu represents the mean of the normal component of the RT distribution. For mu, the repeated measures ANOVA revealed a significant effect for group (ADHD faster than

controls), $F(1, 73) = 6.10, p = .016, \eta_p^2 = 0.077$, and task condition (fixed faster than jittered), $F(1, 73) = 7.16, p = .009, \eta_p^2 = 0.089$, but not for the group-by-condition interaction, $F(1, 73) = 0.667, p = .42, \eta_p^2 = 0.009$ (Figure 1b).

ISV was calculated as the coefficient of variation (CV), which is the standard deviation/mean (Stuss, Murphy, Binns, & Alexander, 2003). For CV, the repeated measures ANOVA revealed significant main effects for group (ADHD more variable than controls), $F(1, 73) = 11.74, p = .001, \eta_p^2 = 0.139$, and task condition (fixed more variable than jittered), $F(1, 73) = 15.96, p < .001, \eta_p^2 = 0.179$, without a significant group-by-condition interaction, $F(1, 73) = 2.42, p = .12, \eta_p^2 = 0.032$ (Figure 2a).

Sigma measures the standard deviation of the normal component of the RT distribution. For sigma, the repeated measures ANOVA revealed significant effects for task condition (jittered more variable than fixed), $F(1, 73) = 3.85, p = .054, \eta_p^2 = 0.050$, but no significant effects for group (ADHD vs. controls), $F(1, 73) = 0.082, p = .775, \eta_p^2 = 0.001$, or group-by-condition interaction, $F(1, 73) = 0.490, p = .486, \eta_p^2 = 0.007$ (Figure 2b).

Tau measures the mean and standard deviation of the exponential component of the RT distribution. For tau, the repeated measures ANOVA revealed significant effects for group (ADHD > control), $F(1, 73) = 6.02, p = .017, \eta_p^2 = 0.076$; task condition (fixed > jittered), $F(1, 73) = 9.50, p = .003, \eta_p^2 = 0.115$; and group-by-condition interaction, $F(1, 73) = 4.54, p = .037, \eta_p^2 = 0.59$. To explore the significant group-by-condition interaction for tau, repeated measures ANOVAs were completed separately within each group, revealing significant effects for condition within the ADHD group (fixed > jittered), $F(1, 44) = 14.48, p < .001, \eta_p^2 = 0.252$, but not among controls, $F(1, 31) = 0.48, p = .494, \eta_p^2 = 0.016$. In addition, between-group comparisons were made within each condition, and revealed significant group differences in tau in the fixed condition (ADHD > controls), $F(1, 74) = 8.23, p = .005, \eta_p^2 = 0.101$, but not in the jittered condition, $F(1, 74) = 1.46, p = .231, \eta_p^2 = 0.020$ (Figure 3).

Across task conditions, the magnitude of group difference was greatest for CV ($\eta_p^2 = 0.139$; ADHD more variable than controls) and smallest for sigma ($\eta_p^2 = 0.001$). Individual logistic regression analyses examining group discrimination for each variable yielded a similar pattern of results in which CV was the strongest discriminating variable—CV: $\chi^2(1) = 8.530, p = .003$, odds ratio (OR) = 75.98; tau: $\chi^2(1) = 8.527, p = .003$, OR = 1.013; SD: $\chi^2(1) = 8.279, p = .004$, OR = 1.011; sigma: $\chi^2(1) = 0.338, p = .561$, OR = 1.005; mean RT: $\chi^2(1) = 0.53, p = .465$, OR = 0.999; and mu: $\chi^2(1) = 4.98, p = .026$, OR = 0.995.

Given the finding of reduced mu and increased errors (omissions and commissions) among children with ADHD, relative to controls, the issue of a speed-accuracy trade-off appeared salient. Therefore, we examined the associations among mu, omissions, and commissions in both test conditions. In the fixed condition, mu and omissions were significantly correlated among children with ADHD ($r = -.403, p = .007$), but not among controls ($r = -.137, p = .462$), whereas in the jittered condition, the associations between omissions and mu were not significant in either group (ADHD: $r = -.183, p = .234$; controls: $r = -.245, p = .185$). A different pattern emerged for commission errors such that significant speed/accuracy

associations were observed in both groups in both conditions. In the fixed condition, the correlation between μ and commissions was significant in both groups (ADHD: $r = -.661$, $p < .001$; controls: $r = -.497$, $p = .004$); in the jittered condition, the association was also significant in both groups (ADHD: $r = -.617$, $p < .001$; controls: $r = -.528$, $p = .002$), suggesting that increased commission errors were associated with faster RTs, regardless of condition or group.

Given the finding of increased τ among children with ADHD, we also examined the relationship between μ and τ , and the relative changes in these variables associated with the jittered condition (compared with the fixed condition). The associations between μ and τ are depicted in Figure 4. In the fixed condition, μ and τ were not significantly correlated among controls ($r = -.086$, $p = .645$); however, the association was stronger (approaching significance) among children with ADHD ($r = -.269$, $p = .077$), suggesting that in children with ADHD, performance lapses tend to increase with faster responses. Furthermore, among children with ADHD, change in τ (i.e., the *reduction* in τ between fixed and jittered conditions) was significantly associated with change in μ (i.e., the increase in μ between fixed and jittered conditions; $r = -.431$, $p = .003$), suggesting that improvement in τ occurred in conjunction with slower responses. Both groups also showed a significant positive correlation for σ and τ under the fixed condition (control: $p = .006$, $r = .486$; ADHD: $p = .005$, $r = .418$), but under the jittered condition, only the ADHD group had a significant correlation ($p = .005$, $r = .413$).

Discussion

The present investigation examined the impact of interstimulus jitter on go/no-go accuracy and RT variability in children with and without ADHD. Consistent with our first hypothesis, we found that children with ADHD showed increased variability (i.e., CV), relative to controls on go/no-go task. Importantly, the findings from the present investigation suggest that this increase in variability is driven by elevation in the exponential (τ), but *not* the normal (σ) component of the RT distribution (Andreou et al., 2007; Kuntsi et al., 2009; Vaurio et al., 2009).

Among children with ADHD, prolonged RTs within the exponential distribution (i.e., elevated τ) likely reflect excessive performance lapses or off-task behaviors (Vaurio et al., 2009). Indeed, ADHD-associated difficulty with sustaining performance, particularly in the context of a repetitive (and boring) go/no-go task, has been hypothesized to be due to difficulty inhibiting attention to more attractive stimuli. Experiments exploring the effects of variations in reward magnitude and immediacy show that individuals with ADHD demonstrate excessive “temporal discounting” with a decrease of subjective reward value as a function of increasing delay (Barkley, Edwards, Laneri, Fletcher, & Metevia, 2001; Bitsakou, Psychogiou, Thompson, & Sonuga-Barke, 2009; Scheres et al., 2006). Incentives improve performance in individuals with ADHD on go/no-go test by decreasing mean RT and variability (Uebel et al., 2010). Therefore, performance lapses (reflected in increased τ) among nonmedicated children with ADHD may reflect a tendency to discount the long-term goal of doing well on the task, and preferentially attend to a more immediately attractive reward, including environmental stimuli or one's own thoughts. Alternatively,

increased tau may be due (at least in part) to the fact that the sustained effort required for the go/no-go task is more unpleasant for children with ADHD, such that the performance lapses reflect an escape from the aversive (boring) task.

We also hypothesized that the introduction of a moderate degree of interstimulus jitter would decrease response variability—especially among children with ADHD. The data also supported this hypothesis. Across groups, introduction of a moderate degree of jitter *decreased* response variability, including normal (sigma) and exponential (tau) components of the RT distribution. Furthermore, when considering the component of response variability that appears to be driven by performance (or motivational) lapses (i.e., tau), the introduction of jitter served to reduce these lapses among children with ADHD to a much greater degree than among controls, such that in the jittered test condition, there was no significant difference in tau among children with and without ADHD. Conversely, this same pattern of differential response to jitter among children with ADHD was not observed for the normal component of the RT distribution (sigma). Recent work by Epstein et al. (2011) and Uebel et al. (2010) suggest that event rate manipulation does not significantly affect ADHD performance differentially when compared with controls; however, these studies applied a fixed ISI (with faster or slower rates), rather than manipulating the ISI via jittering throughout an entire trial. The present findings imply that variability in stimulus presentation increases consistency of motor responses, resulting in decreased variability within the normal RT distribution curve and reduced lapses in performance (i.e., decreased tau) for individuals with ADHD. In sum, we found that jittering ISI decreased sigma and tau, resulting in greater consistency between RTs and a reduction in extreme lapses in on-task behavior. The effect of jitter was particularly strong for children with ADHD, as decreases in variability are principally caused by a reduction in the number of the outlier responses characteristic of poor response control in ADHD under fixed testing conditions. To our knowledge, this is the first study to apply an ex-Gaussian approach to demonstrate the effect of moderate ISI jitter in improving response control deficits in children with ADHD.

The Gaussian analysis of mean RTs does not identify any significant differences between groups (ADHD vs. controls), test conditions (fixed vs. jittered), or between conditions within each group, perhaps because the mean RT variable included outlier responses. In contrast, the ex-Gaussian analysis revealed lower mean RTs in the normal distribution (μ) for the ADHD group compared with controls when outlier responses were controlled. It therefore appears that after accounting for the increased occurrence of very slow RTs, children with ADHD actually show *faster* responses than controls on these go/no-go tasks. This faster response speed is associated with increased omission errors (suggesting a speed-accuracy trade-off), but only in the (boring) fixed ISI condition, and not when the ISI is jittered. Conversely, stimulus jittering does not affect the manifestation of the speed-accuracy trade-off for commission errors, as a significant association between faster RT and increased commissions was observed in both groups, regardless of task condition. Jittering may, however, produce a speed-variability trade-off, such that jittering induces decreased variability and fewer outlier RTs (lower tau), resulting in slower mean RT in the normal distribution (higher μ). Under the fixed condition, children with ADHD show a bias toward speed as opposed to consistency, with faster RTs in the normal distribution (lower

mu), but greater variability with excessive outlier RTs (higher tau) as compared with controls. Thus, among children with ADHD, jittering appears to shift the bias in response control, increasing consistency by minimizing outlier RTs while decreasing mean RT.

Jittering appears to provide a nonpharmacologic mechanism to facilitate readiness to respond to a stimulus and reduce extreme momentary lapses from on-task behavior. This effect may be a function of increased activity of dopaminergic and/or noradrenergic circuits that maintain frontal networks critical to attention and response control. Both “top-down” mechanisms mediated by prefrontal circuitry and “bottom-up” mechanisms facilitated by external manipulation in tasks designed to increase vigilance through activation of noradrenergic projections of the locus coeruleus have been proposed (Berridge et al., 2006; Krawczyk, 2002; Sergeant, Geurts, Huijbregts, Scheres, & Oosterlaan, 2003). Jitter may also reduce variability through dopaminergic projections. There is substantial evidence that ADHD behaviors are associated with dysfunction of dopaminergic reward systems (Borger & van der Meere, 2000; Groom et al., 2010; Liddle et al., 2010; Rubia et al., 2009; Volkow et al., 2010). The current pattern of findings suggests that jitter may increase the novelty of stimulus presentation, thus increasing phasic dopamine release in anticipation of a reward, and for individuals with hypoactive dopaminergic reward systems (such as in ADHD). This effect is particularly beneficial for normalizing performance on a response-time task.

In summary, ADHD is a neurobiological abnormality associated with genetic and/or environmental influences (Castellanos et al., 2002). Mechanisms remain elusive because of the complex nature of these cognitive processes. Several critical executive function skills, including sustained attention, inhibition of off-task behavior, and preparedness to respond are intermediate steps between stimulus perception and the choice of when and how to respond (Denckla, 1996). Nonpharmacologic modulation of these interconnected networks may provide an alternative to pharmacologic therapy or serve as adjunct therapy. Many questions remain, including whether synergy exists between pharmacologic and nonpharmacologic interventions, and whether jittering affects RT variability in other disorders of cognition. The mechanisms underlying the jitter effect remain rich areas of study. Expanded models of the jitter paradigm include varying the degree of jitter and application of jitter to education-based learning strategies. Further studies should explore the effect of jitter on improving sustained attention (e.g., reading fluency) and other ADHD functional impairments.

Strengths of this study include the application of ex-Gaussian methodology, relevance for current biological models of ADHD, and the potential for application in the academic setting. Limitations of this study include the use of single-degree “moderate” jitter, rather than higher or lower degree of jitter, which may broaden the scope of applicable variability between presented stimuli. In addition, the ex-Gaussian approach to analysis of RT data does not take into account the impact of response accuracy on RT variability and, as such, may not fully characterize the psychological processes (attentional lapses) that it is intended to represent (Matzke & Wagenmakers, 2009). Finally, the present sample was relatively restrictive in its operationalization of ADHD, thus the generalizability of the present study's findings to children with ADHD and commonly cooccurring conditions such as language disorder or learning disability is questionable. The present sample was also not taking

stimulant medication at the time of testing—Future research should investigate the impact of stimulant medication use on attentional lapses such as those identified in this study. Revealing abnormalities in the neural systems coordinating response preparation is critical for understanding the biological basis of ADHD. Although increasingly complex, our knowledge describing human cognition and behavior is advancing. The ex-Gaussian method represents one comprehensive approach for studying RT variability. As reported in this study, interstimulus jitter may be a good candidate for a nonpharmacologic approach to improve response preparation efficiency in ADHD. As our understanding of the influences underlying the genetic and physiologic substrates of attention and response control improves, application of novel test paradigms such as jitter may result in improved outcomes for individuals with ADHD.

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Lisa A. Jacobson, PhD, is a clinical neuropsychologist and licensed psychologist in the Department of Neuropsychology at the Kennedy Krieger Institute in Baltimore, Maryland. She is also an instructor in the Department of Psychiatry and Behavioral Sciences, Johns Hopkins University School of Medicine. She received her PhD from the University of Virginia, Curry School of Education in 2008, and completed her postdoctoral fellowship in pediatric neuropsychology at the Kennedy Krieger Institute. She is also a nationally certified school psychologist. Her clinical and research interests focus on childhood disorders affecting the development of executive functions, particularly with regard to the effect of executive dysfunction on daily functioning within academic settings.

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Figure 1.

Group differences in mean response time (ms) by group across task conditions

Note: (a) The mean reaction time in ADHD is faster compared with controls under both conditions, but these effects did not reach statistical significance. (b) Ex-Gaussian analysis demonstrates that under the fixed condition ADHD was faster than controls, but there was no significant effect for groups by condition. Bars represent standard error.

Figure 2.

Intrasubject variability of response time by group across conditions

Note: CV = coefficient of variability. (a) ADHD subjects showed significantly higher CV than controls under the fixed condition, but there was no significant group by condition interaction. (b) Under the fixed condition, both groups showed higher sigma, but there was no effect between groups, or interaction for groups by condition. Bars represent standard error.

Figure 3.
Group differences in tau across task conditions
Note: Bars represent standard error.

Figure 4.

Scatterplots of correlation between mu and tau by group and condition: (a) In the fixed condition, the correlation between mu (mean response time) and tau (outlier responses) was nonsignificant across groups (ADHD: $p = .07$, $r = -.269$; control: $p = .645$, $r = -.086$) and (b) change in tau (the difference between test conditions: jittered minus fixed) was significantly correlated with change in mu for ADHD but not controls (ADHD: $p = .003$, $r = -.431$; control: $p = .348$, $r = -.174$)

Table 1

Sample Demographic Characteristics

	Control (<i>n</i> = 31)		ADHD (<i>n</i> = 44)		<i>t</i>	<i>p</i>
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>		
Age (years)	11.23	1.44	11.16	1.57	0.183	.855
SES	47.99	14.92	45.76	16.10	0.603	.548
FSIQ	116.13	10.01	99.52	13.34	5.859	<.001
VCI	112.68	13.37	101.55	12.06	3.764	<.001
CPRS-R/DSM-IV Inattentive (<i>T</i>)	47.42	7.42	72.16	8.47	-12.30	<.001
CPRS-R/DSM-IV Hyperactive/Impulsive (<i>T</i>)	47.31	6.20	72.47	13.24	-9.08	<.001
CPRS-R/DSM-IV total score (<i>T</i>)	47.35	7.46	74.35	9.76	-12.11	<.001

Note: SES = socioeconomic status; FSIQ = Full Scale IQ; VCI = Verbal Comprehension Index; CPRS-R = Conners' Parent Rating Scale-Revised; DSM-IV = *Diagnostic and Statistical Manual of Mental Disorders* (4th ed.); *T* = *T*-score.

Table 2

Errors, Gaussian, and Ex-Gaussian RT (ms) Values Across Condition by Group

	Control (<i>n</i> = 31)		ADHD (<i>n</i> = 44)	
	Fixed (<i>SD</i>)	Jittered (<i>SD</i>)	Fixed (<i>SD</i>)	Jittered (<i>SD</i>)
Omissions	1.93 (2.43)	2.54 (2.89)	4.62 (5.71)	3.74 (4.36)
Commissions	22.11 (16.17)	23.16 (18.34)	33.36 (20.71)	34.67 (19.22)
Mean RT	455.23 (135.74)	464.35 (133.97)	435.66 (97.92)	431.95 (70.74)
CV	0.30 (0.16)	0.26 (0.70)	0.42 (0.17)	0.31 (0.11)
Mu	354.36 (130.74)	369.27 (103.93)	296.04 (93.98)	324.05 (52.95)
Sigma	59.46 (31.84)	55.53 (32.75)	63.38 (27.10)	55.08 (25.75)
Tau	100.88 (49.48)	95.08 (38.19)	139.62 (62.65)	107.90 (49.59)
RT <i>SD</i>	133.97 (59.37)	118.65 (42.85)	178.14 (68.96)	135.35 (60.01)

Note: RT = response time; *SD* = standard deviation; Omissions = percent omission errors; Commissions = percent commission errors; CV = coefficient of variability (RT *SD*/mean RT); Mu = mean, ex-Gaussian; Sigma = *SD*, ex-Gaussian; Tau = mean and *SD*, ex-Gaussian.